ESTCP
Cost and Performance Report

(WP-200819)

Ultrasonic Guided Wave Technology for Non-invasive Assessment of Corrosion-induced Damage in Piping for Pollution Prevention in DOD Fuel Storage Facilities

September 2011

ESTCP

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ACRONYMS AND ABBREVIATIONS

API	American Petroleum Institute
CFR	Code of Federal Regulations
CSAL	cross-sectional area loss
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
FISC	Fleet Industrial Supply Center
NDE	Nondestructive Evaluation
NSWCCD	Naval Surface Warfare Center Carderock Division
OD	outside diameter
OPA	Oil Pollution Act
OSHA	Occupational Safety and Health Administration
SEAP	Science and Engineering Apprentice Program
VP	Valve Pit

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1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES OF THE DEMONSTRATION

Corrosion-induced defects in long and inaccessible pipelines are a concern for the Department of Defense (DoD) because of the potential for leaks and oil spills on land and underwater caused by metal corrosion. Current practices of inspection techniques allow seriously deficient items to be repaired or removed from service, sometimes at inconvenient times and high cost as a result of emergencies. However, none of these techniques provides sufficient information to predict the growth rate of small defects. This report summarizes the work performed in a two-phase Environmental Security Technology Certification Program (ESTCP) project to demonstrate the capabilities of commercially available ultrasonic guided wave technology for the detection, sizing, and growth monitoring of corrosion-induced defects in fuel piping.

1.2 TECHNOLOGY DESCRIPTION

Contrary to conventional ultrasound, which by equipment design excites wave propagation through the thickness of a material, guided wave ultrasound in a pipe propagates along the axis of the pipe over a long distance. By analyzing the reflections from defects at a long distance, the location and the severity of the defects can be determined by suitable calibration techniques. We seek to demonstrate that ultrasonic guided wave technology can be a noninvasive, cost-effective technology that not only detects defects but also monitors their growth rate without additional measurements. We attempted to demonstrate that this can be achieved by simply recording the changes in ultrasonic guided wave signals periodically.

1.3 DEMONSTRATION RESULTS

In Phase I, a pipeline was established in the facilities at the Naval Surface Warfare Center, Carderock Division (NSWCCD), incorporating welds, elbows, and hidden corrosion-induced defects to serve as a test bed for ultrasonic guided wave technology. Results demonstrated that a defect growth rate could be established based on ultrasonic signal characteristics and established the viability of this technology to monitor defect growth in pipelines in the field. This technology was demonstrated in Phase II in a steel pipeline at Norfolk Naval Station, Norfolk, VA. Transducers were installed on above and below ground pipe sections of mixed 10-inch, 8-inch, and 6-inch outside diameter piping with numerous bends, welds, and reducers. Access points aboveground allowed convenient monitoring of pipeline conditions over a period of 20 months. We monitored the achievable inspection distance, the stability of signals in variable environments, defect detection, and defect growth. It is concluded that there has not been sufficient corrosion occurring to produce a wall cross section loss exceeding 30%, an indirect indication of the efficacy of the cathodic protection system for the pipeline. Compared to the Phase I results, the signal-to-noise ratio in the old pipeline in the field was larger by a factor of four in most locations. Several locations suspected of having corrosion have not yet produced consistently increasing ultrasonic signals to warrant excavation and physical examination. It is recommended that monitoring be continued to further demonstrate this technology for future DoD and commercial use.

1.4 IMPLEMENTATION ISSUES

Some of the performance objectives have not yet been met in the monitoring duration of 20 months because natural corrosion occurs slowly and since insufficient information is available on the physical construction of the different sections of the pipeline, which could have served as location and defect calibration markers. We recommend that a method to select promising locations for condition monitoring using permanent sensors in a pipeline should be preceded by a preliminary evaluation for weld signal response using remountable transducers. Additionally, locations where weld signals are well above noise level in the baseline should be identified first to enhance the success of defect growth monitoring later on. Extensive planning for the selection of measurement points is necessary to achieve good results. Mostly, the cost is associated with the labor hours for the testing and subsequent data analysis. Preliminary demonstrations of this technology are underway in Navy fuel storage and transport facilities in Marine Corp Base Quantico, VA, and Fleet Industrial Supply Center (FISC), Mayport, FL.

2.0 INTRODUCTION

The Oil Pollution Act (OPA) of 1990 sets up operational and maintenance requirements for DoD and civilian fuel/oil storage and transport facilities in the United States Fuel/oil spills are problematic for DoD in terms of impacts to the environment, costs in cleanup, and adverse public perceptions. Since pipeline problems resulting in leaks and spills can be caused by metal corrosion, devices known as maintenance pigs and smart pigs are passed through a pipeline to measure wall thickness loss and other structural anomalies. In addition, leak indicating pressure testing and excavation to expose the surface of buried pipes for visual inspection are also used. These techniques do not provide sufficient information to predict the future health of the piping unless a failure leading to leakage has already occurred.

This report summarizes the results obtained in Phase I and II of an ESTCP-supported project from 2008 through 2011. A test facility was established in Phase I at NSWCCD for pipes with controlled amounts of corrosion damage before field testing in a live pipeline in Phase II.

2.1 BACKGROUND

Corrosion in steel piping in DoD fuel storage and transport facilities can lead to fuel leaks and potentially serious spills if it is not detected to allow for timely repair. This problem is compounded by the fact that piping systems can extend for many miles and often go underground through dikes and road crossings, making them inaccessible for routine inspection. Current practices of inspection techniques allow seriously deficient items to be repaired or removed from service, sometimes at inconvenient times and high cost as a result of emergencies. However, none of these techniques provide sufficient information to predict the growth rate of small defects. Often, the presence of defects does not imply the end of life of the structure. As long as the changes in these defects can be monitored, it could be economical to continue using the existing structures until the point is reached when they are judged to be unsafe to be used.

2.2 OBJECTIVE OF THE DEMONSTRATION

We seek to demonstrate that ultrasonic guided wave technology can be a noninvasive, cost-effective technology that not only detects defects but also monitors their growth rate without additional measurements. The overall objective of this ESTCP project was to demonstrate and validate this capability in the field.

2.3 REGULATORY DRIVERS

OPA (1990) established the laws governing oil spill prevention and response on both the federal and state levels. Management plans are in place at Navy fuel storage and transport facilities, in accordance with the guidelines provided by 94 Code of Federal Regulations (CFR) Chapter 195, Pipeline Safety, and Pipeline Management in High Consequence Areas. To achieve compliance, pipeline inspection is performed periodically and corrective actions are taken to prevent fuel/oil spills. Ultrasonic guided wave technology is included by the American Petroleum Institute (API) as one of the new tools for safety inspection of a pipeline as stated in API 570 procedures.

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3.0 DEMONSTRATION TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

Conventional ultrasound technology is commonly used for nondestructive material evaluation and in the health care industry. For that reason, guided wave ultrasound is a special variant of this technology. Contrary to conventional ultrasound, which by equipment design excites wave propagation through the thickness of a material, guided wave ultrasound in a pipe propagates along the axis of the pipe over a long distance, as shown in the sketch in Figure 1. By analyzing the reflections from defects at a long distance, the location and the severity of the defects can be determined by suitable calibration techniques (Liu et. al., 2008; 2006).

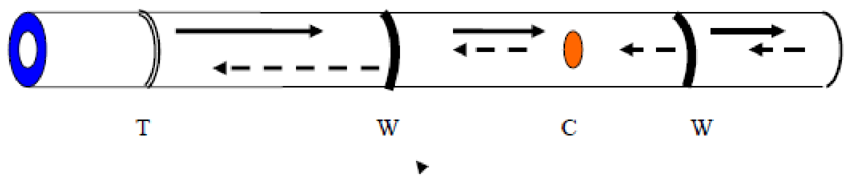


Figure 1. Sketch of ultrasonic guided wave propagation in a pipeline.
T represents the transducer for launching and receiving wave signals,
W represents the welds, and C represents an area of corrosion.
Right-going arrows depict waves launched by the transducer and left-going arrows depict reflections from the welds, corrosion, and the end of the pipe.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The maintenance for piping integrity in DoD fuel storage and transport facilities and ships is currently based on either a time-based schedule (preventive maintenance) or in response to an emergency following an incident of piping failure (corrective maintenance). While the current practice of using smart pigs for condition assessment is effective for very long pipelines, it is expensive and interrupts pipeline operations. Furthermore, results obtained by smart pigging today do not provide information on the rate of corrosion-induced wall loss in the future. Set up cost (at tens of thousands of dollars) for smart pigging is high, rendering it impractical for a short line. Also, hydrostatic tests are used frequently today (at a cost of $5000 to $50,000 per test) to verify the structural integrity of a pipeline. Part of this test actually relies on inducing a visible controlled leak in the weak points (likely caused by corrosion) along the line, at which point repair or replacement of the weak sections is then carried out. If the technology of guided waves can be demonstrated to provide reliable information not only on sizing the defects but also on defect growth rate, it will provide timely information to facilitate the practice of predictive maintenance in fuel facilities at low cost. In addition, many short lines can be tested in one work day by a qualified inspector at a cost of less than $2000.

Drawbacks do exist in the ultrasonic guided wave technology. First, guided waves do not propagate beyond a flange in the pipeline. The choice of access points for launching and receiving guided waves must take into account the locations of flanges, valves, elbows, and other obstructions, which sometimes prevent inspection of parts of a pipeline. The second

limitation/drawback is some uncertainty in the smallest amount of corrosion-induced wall loss in a complex piping system that can be detected by the proposed monitoring techniques. Today, commercial testing services show that an averaged loss of 10% in wall cross-sectional area can be reliably detected in the field in 50-100 ft long pipes. The effect of old, unknown, and protective coatings on inspection distance is another aspect that can only be assessable by on-site measurements.

4.0 PERFORMANCE OBJECTIVES

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
1. Achievable inspection distance	Pulse-echo signal traces for pipeline at start of the project	100 ft from transducer location	In field testing, distance up to 92 ft, but most frequently at approximately 30 ft from transducer
2. Stability of signal traces and durability of transducers	Location and peak height of weld signals over the course of the project	Distance and peak height reproducible to within 5%	Peak height reproducible at 30 ft to within 10% over 20 months
3. Accuracy in locating defects in pipelines in a Navy fuel storage facility using ultrasonic guided wave technology	Results of visual or other conventional nondestructive evaluation (NDE) measurement at locations identified by ultrasonic guided waves, or data provided by pigging, or by observations after underground pipes are exposed	Accuracy of locating a defect within +/-2 ft at a distance of 50 ft from the location where ultrasonic waves are launched	Weld signal locations stationary to within +/-2 ft at 30 ft. Physical sighting of defects not yet available
4. Minimum size of detectable defect based on guided wave ultrasound	Ultrasonic signals including background noise returned from a distance of up to 50 ft	A defect with 10% cross-sectional area loss (CSAL) at 50 ft is detectable	10% CSAL at 20-30 ft
5. Accuracy in sizing defects	Data on sizes of defect and the corresponding ultrasound data	Defect sizing is accurate to within a factor of 2	Physical examination of defects not yet available
6. Capability for defect growth monitoring	Changes in ultrasonic signals as a function of time	Defect size increase by 10% CSAL resulted in changes in signal peak height above noise level	Consistent signal increases indicating defect growth await further monitoring; signal for 10% CSAL probably achievable at 20-30 ft
7. Improved planning for maintenance activities	Data on repair activities and incidence of corrosion induced piping failures	Sufficient time (3 months or more) is provided for budgeting and planning for piping repair before any failure due to corrosion	Defect large enough to warrant repair has yet to be detected; objective to be demonstrated by additional monitoring time
8. Increased efficiency in pipeline maintenance as a result of the use of ultrasonic technology	Maintenance activity records	Redistribution of the limited, invasive maintenance resources from one pipeline to another or from one part of a pipeline to another as a result of increased confidence in the conditions of the pipelines provided by ultrasonic data	Awaiting additional monitoring effort; no piping failure or leakage is observed during 20 months of monitoring
9. Technology maturation	Data on the use of technology by DoD	Increase in the application of technology in DoD since the initiation of this project in 2008	New equipment has been developed commercially and demonstrated in Navy facilities since start of this project

Because excavation is very disruptive to site operation, we recommended to proceed only when the results of ultrasonic tests suggest the existence of defects with a CSAL of 30% or larger, in order to allow repair action to proceed well before a defect size reaching 50% CSAL which is the current commercial standard. For this reason, a suspected region would be available for visual or other inspection for damage sizing only when it reached a later stage of damage. In our plans for the field tests, the relationship between the ultrasonic data and the location and sizes of small defects was intended to be an extrapolation from the results for the larger defects. This and other aspects of defect sizing will be discussed in later paragraphs.

5.0 FACILITY/SITE DESCRIPTION

5.1 PHASE I LABORATORY SITE

In Phase I, a pipe loop with both indoor and outdoor sections was housed in a long building for corrosion and ultrasonic guided wave experiments in the facilities at NSWCCD in West Bethesda, MD.

5.2 FIELD TEST SITE SELECTION

The Navy fuel facility at Norfolk Naval Station, Norfolk, VA, was selected as the demonstration site. This site has an underground pipeline and underground storage tanks. It is part of a large FISC based at Craney Island, Portsmouth, VA. The fuel department manager and staff are supportive of the proposed demonstration, since they are interested in new technology such as ultrasonic guided waves to identify existing areas of corrosion and other structural weakness in the inaccessible sections of the pipeline.

5.2.1 Site Operation

This Navy site is operated by the Naval Supply Systems Command. It supplies mainly JP-5 jet fuel for Navy aircrafts based on land and onboard ships. In addition to federal civilian employees, it is supported by on-site contractors for operations and maintenance. This includes the upkeep of valve pits that provide access to the underground pipeline.

The general layout of the pipeline where the majority of the test was performed is shown in Figure 2. The total length of the pipeline between Valve Pit (VP) 5 and VP 7 is approximately one mile. Please note, there are several abrupt bends in the pipeline between VP 5 and Block 20. The distance between each valve pit is approximately 200-400 ft, with a longer distance of approximately 2000 ft between VP 23 and VP 7. The pipeline runs underground through the Navy base from VP 7 to the underground storage tanks in Chambers Field, approximately 3 miles away.

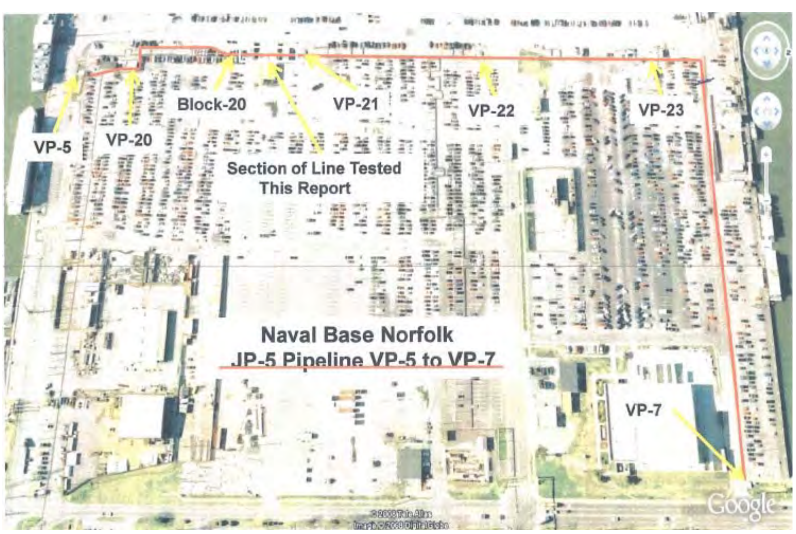


Figure 2. JP-5 pipeline layout (shown in red) **from VP5 to VP7 at Norfolk Naval Station.**

5.2.2 Site Conditions

JP-5 jet fuel in storage tanks on Craney Island supplies the needs of Navy aircrafts at Naval Station Norfolk via this pipeline that runs through the Elizabeth River before reaching the shores in Norfolk. Sections of the pipeline between VP 5 and VP 7 were deemed unpiggable because of the existence of internal obstructions and reducers and because of cost considerations for a relatively short line. An example of obstructions inside a valve pit is shown in Figure 3.

Figure 3. Pipeline accessories inside a valve pit.

A section of the pipeline between Block 20 and Valve Pit 21 was replaced 4 years ago because of structural weakness as revealed by pressure testing. It has a mixture of 10-inch and 6-inch pipes connected through reducers and valves.

5.2.3 Site Related Permits and Regulations

We secured the permission from the Navy site manager to conduct the proposed guided wave technology demonstration. To comply with Occupational Safety and Health Administration (OSHA) regulations workers inside valve pits completed safety training for confined space environment. Federal and state regulations require valve pits to be certified by qualified safety professionals daily before humans are allowed to work inside. DoD staff and contractors have complied with the requirements that a team of two people should work together inside a valve pit. In addition, a third person is to be present outside on safety watch when workers are inside a pit.

6.0 TEST DESIGN

In Phase I, government staff controlled the corrosion experiments, including the location and severity of the defects, measured the defect characteristics, and examined, as well as analyzed the ultrasonic guided wave data provided by the inspectors. The locations of the defects were hidden from the inspectors throughout the defect growth monitoring effort to simulate the unknown conditions in the field. In Phase II, field testing at Norfolk Naval Station the existence of defects was unknown. Detailed test design is shown in later paragraphs.

6.1 CONCEPTUAL LABORARY TEST DESIGN (PHASE I)

6.1.1 Pipeline Design and Layout

The pipeline in Phase I was 8.6 inches outside diameter (OD), 0.33-inch thick (8-inch schedule 40) steel pipe, set up as shown in Figure 4. In addition to a number of welds, we incorporated two 90 degree elbows joined by a 5 ft long pipe segment, with 75 and 25 ft long straight segments extending to the other ends. The intent was to provide sensor placement areas that allow the investigators to test their equipment in both straight and elbow contained pipe sections before reaching a defect.

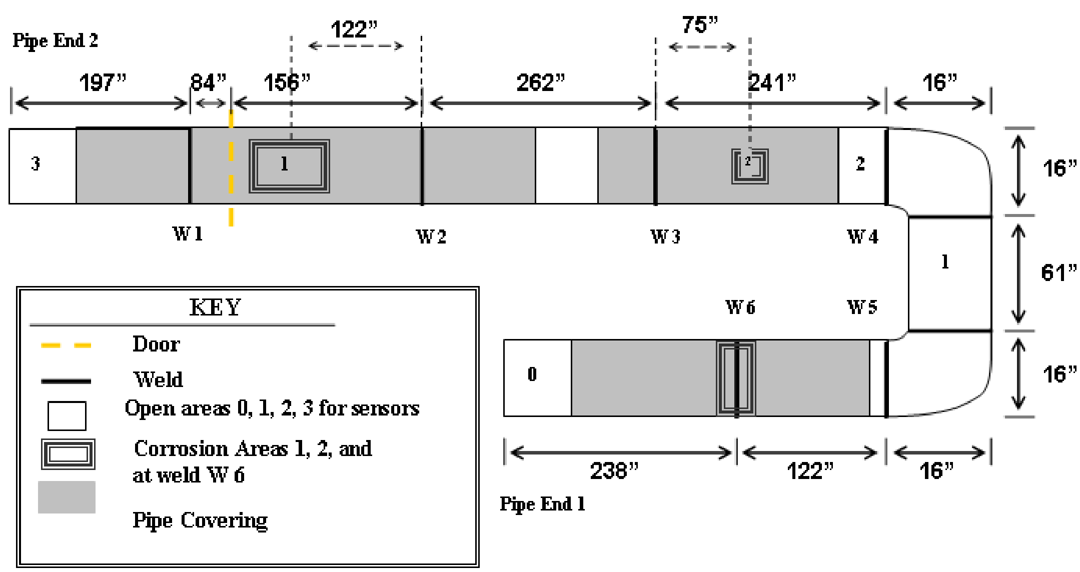


Figure 4. Location of ultrasonic measurement points and corrosion defects in the 8.6-inch diameter pipeline at NSWCCD.

The nominal 20 ft long pipe segments were coated by a three layer protective paint, following the Unified Facilities Guide Specification for an outdoor, aboveground environment. A 20 ft segment of the pipeline was left outdoors to provide some indication of the performance of transducers left in the outdoor environment. The rest of the pipeline was housed in a long indoor space where controlled corrosion experiments and ultrasonic measurements were made. The pipeline was supported every 10 ft by pipe stands, and the pipe stands were electrically isolated from the pipeline to reduce potential interference with the testing.

6.1.2 Defect Locations and Size

Figure 4 illustrates the locations of the corrosion-induced defects. Two defects (unknown to the inspectors) were placed in the long straight sections of the pipeline. One of the defects not only increased systematically in its depth, but also along the pipe axis and along its circumference as the exposure progressed (Defect 1). The other defect was intended to be a ”small” defect (Defect 2) having a fixed lateral dimension of approximately 3×3 inches, but with increasing material loss in the thickness direction. The goal was to achieve a wall thickness loss exceeding 50% in this defect by the end of Phase I.

6.1.3 Transducer Placement

In Figure 4, regions 0, 1, 2, and 3 show where transducers were mounted. We see that waves excited by Sensor 3 propagating in the negative direction should reach Defects 1 and 2 before reaching an elbow. Waves excited by Sensor 2 propagating in the positive direction should reach Defects 2 and 1 before it reaches the pipe end. Waves excited by Sensor 1 should see Defects 2 and 1 after crossing an elbow in the positive direction and see the Defect W6 in the negative direction after crossing an elbow. Waves excited by Sensor 0 and propagating in the positive direction sees Defect W6 before reaching either elbow and beyond.

6.1.4 Definition of Cross-Sectional Area Loss

An important measure, widely used in the industry for characterizing the degree of corrosion damage in a pipe is the CSAL. Its definition is shown in a sketch in Figure 5. Other useful measures include the averaged depth of material loss and the total volume loss in a damaged region in the pipe wall. Signal peak height will be correlated to these measured quantities in later parts of this report.

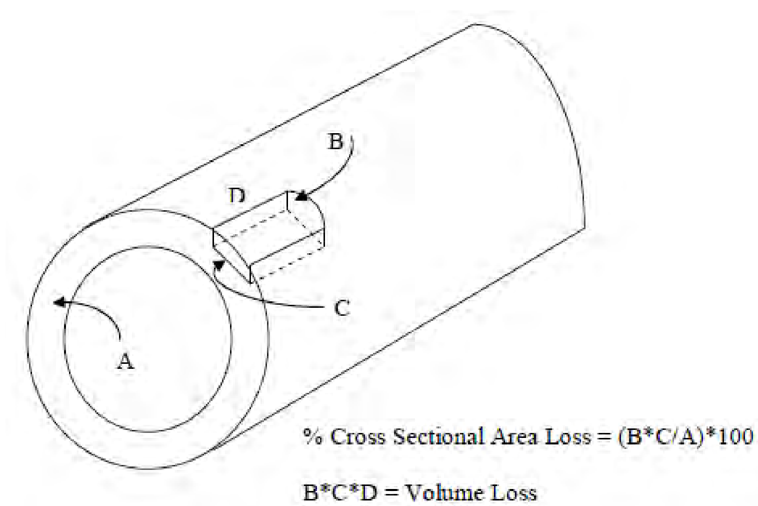


Figure 5. Definition of CSAL and volume loss.
A is the cross-sectional area of the pipe wall, B is the average depth of corrosion, C is the length of the corroded area along the circumference of the pipe, and D is the length of the corroded area along the length of the pipe.

6.2 FIELD TEST DESIGN (PHASE II)

6.2.1 Conceptual Test Design

In the field testing, we drew upon experience gained in Phase I for ultrasonic tests in pipes undergoing controlled corrosion. Of interest in the field testing were the capabilities in defect detection, sizing, and growth monitoring, as well as the repeatability of data in changing environment, the durability of transducers, and the consistency of test results obtained by pigging (if available) and by ultrasound.

We had ultrasonic guided wave transducers permanently mounted at selected pipe sections that were either above ground or were exposed inside valve pits. These transducers were powered via extension cables by equipment that remained aboveground and were accessible at convenient locations on the pit wall. These transducers were accessible for the duration of this project. In general, wave propagation in both the forward and backward directions was attempted in order to maximize the range of pipe coverage, unless the existence of a flange obstructs wave propagation along a particular direction.

Electronic equipment was energized by power sources transported in an automobile from one location to another. The ability to do monitoring without reentering the valve pits had two benefits. First, the requirements for confined space entry were met only for the baseline measurement when the transducers were installed inside the valve pits. Secondly, this eliminated the need for repeated personnel entry to valve pits which had an opening of approximately 2 by 3 ft only.

6.2.2 Baseline Characterization

Since the baseline information on the rest of the pipeline extending from VP 5 to the rest of the pipeline was unknown, the results of the initial guided wave measurements in August 2009 served as the baseline data.

6.2.3 Design and Layout of Technology

The ultrasonic guided wave measurement system started with bonding magnetostrictive metal strips to the pipe surface by room-temperature cured epoxy. This was preceded by the removal of protective coating from the pipe surface and the removal of debris and rust by hand sanding and brushing. Examples of surface conditions on an above-ground pipe section and one inside a valve pit are shown in Figure 6. Protective duct tape was applied to these strips after transducer bonding. Low profile, energizing coils were wrapped around the bonded strips before tar-based, roofing compound was applied. The electrical leads to coils were brought outside of a valve pit into an access port mounted on the external wall for easy access, as shown in Figure 7. Experience showed that a “transducer assembly” fabricated in this manner had been environmentally stable for up to 5 years in outdoor environment. Each transducer was bar-coded for easy identification.

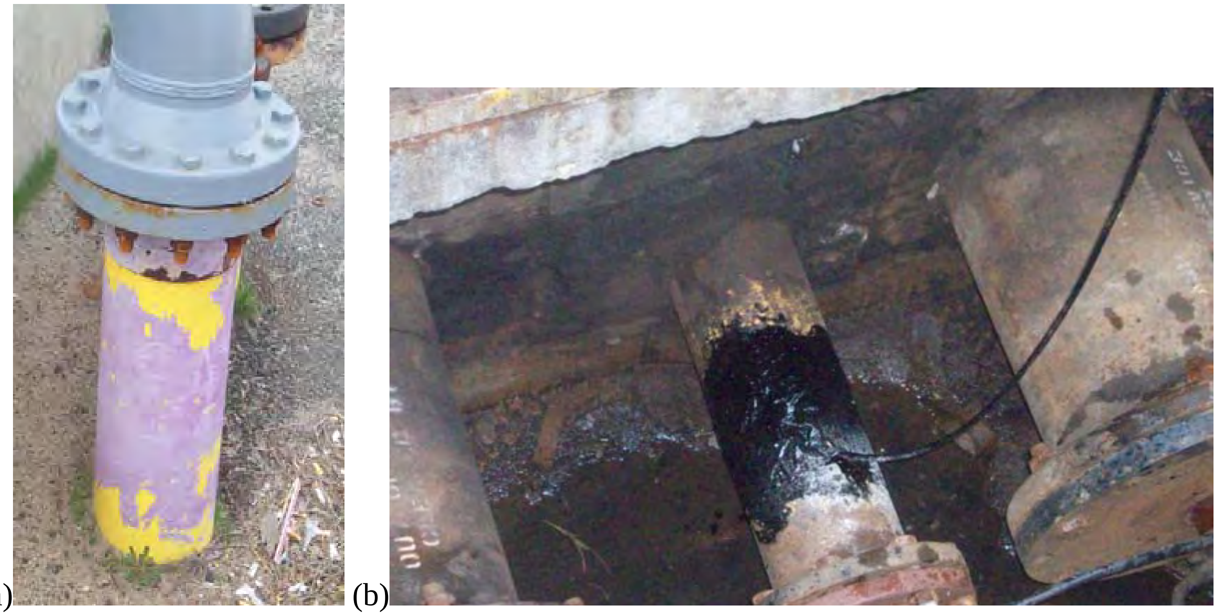
(a) (b)


Figure 6. Surface conditions of tested pipe.
(6a) Protective paint on a section of pipe to be removed prior to transducer mounting
(6b) Protective tar coating and lead wires for a transducer in the underground pipeline

Figure 7. Access boxes for signal monitoring outside of restricted areas around VP5.

6.2.4 Operational Testing

After baseline measurements following transducers installation in August 2009, follow-up monitoring was performed in January 2010, September, 2010, and April 2011. More frequent follow-up measurements would have been warranted if the initial data sets suggested the existence of significant corrosion damage in part of the pipeline. In that case, corrective maintenance activity may be recommended. Our intent was to monitor the changes in the pipeline, which would progress moderately slowly, unless the guided wave data suggested otherwise. Observations by on-site contractors were also made to assess the conditions of the electronic outlet boxes and to record water accumulation inside VPs.

6.2.5 Equipment Calibration

The key guided wave signal parameters upon which judgment for the location and the severity of a defect is based are the time of arrival, the peak height, and the shape of the signal envelope. In the field, the consistency of time measurement was checked by noting the time of wave arrival from known markers such as welds and flanges.

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7.0 PERFORMANCE ASSESSMENT

7.1 LABORATORY RESULTS (PHASE I)

7.1.1 Cross-Sectional Area Loss

As stated earlier, we obtained a statistical average of area loss by taking photographs of the corroded areas and identifying a large number of locations where micrometer readings should be made. These readings allowed the calculation of a good statistical average of the overall area loss at each stage of corrosion.

Table 2. Summary of corrosion defect characteristics.

Defect	Month	Size (Circ)×(axial) in	CSAL (%)*(Ave+/-stdev) %	Wall Thickness Loss[2] (Ave+/-stdev) in	Volume Loss (Ave+/-stdev) in^3
2	June	~ 3×3	1.8+/-0.2	0.06+/-0.007	0.6+/-0.08
	August	3×3.5	3.2+/-0.12	0.09+/-0.006	0.96+/-0.06
	September	3×3.5	8.8+/-0.7	0.23+/- 0.02	3.5+/-0.28
	December	4×4.5	11.6+/-1.7	0.26+/-0.04	4.7+/-0.7
1	June	5×11	3.6+/-0.39	0.06+/-0.007	3.6+/-0.38
	August	5×11	5.2+/-1.0	0.09+/-0.006	5.1+/-0.33
	September	11×12	9.4+/-0.5	0.07+/-0.004	10.3+/-0.55
	December	12×15	14.0+/-0.9	0.11+/-0.007	18.7+/-1.2
W6	June	6×3.5	4.5+/-0.8	0.07+/-0.03	1.4+/-0.09
	August	6×3.5[1]	12.8+/-6.0	0.2+/-0.1	4.2+/-0.4
	September	10.5×3.5[1]	13.5+/-1.4	0.13+/-0.07	4.0+/-0.2
	December	12×4[1]	25.0+/-1.2	0.2+/-0.08	8.8+/-0.3

Notes:
Pipe wall cross-sectional area = 32.7 square inches
[1]Crack developed
[2]Nominal wall thickness = 0.335 inches
Defect 2 is 65 ft from Pipe End #2
Defect 1 is 26 ft from Pipe End #2
Defect W6 is the weld defect, 20 ft from Pipe End #1

7.1.2 Ultrasonic Data

An example of ultrasonic guided wave data showing peak height versus distance along the pipeline (see Figure 4) is shown in Figure 8. Wave propagation speed has been utilized to convert time of flight information to distance information along the pipe. In this figure, the large peaks are reflections from the welds. We note the existence of some small signal peaks with unknown origin before the initiation of corrosion that are not associated with welds. They could be caused by pipe stands, as-manufactured material anomalies, or other unknown conditions. We will come back to these points later in this report.

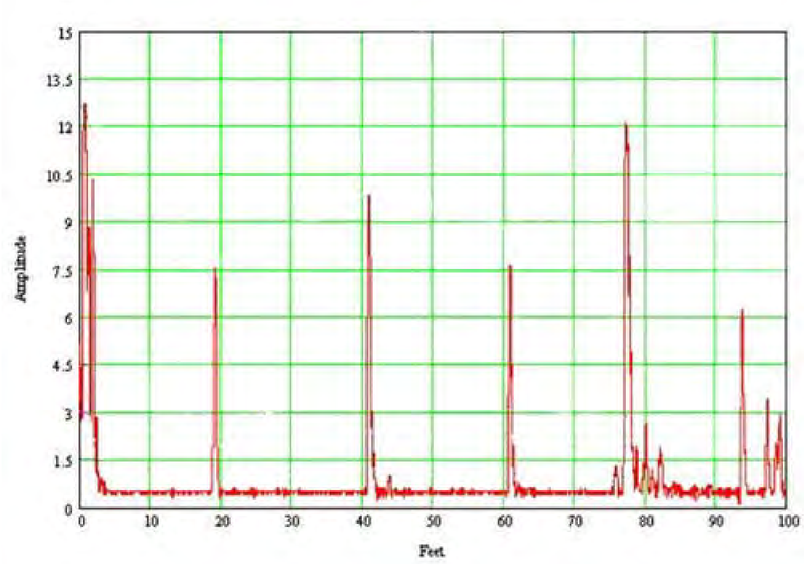

Figure 8. Example of plotted ultrasonic guided wave baseline data for the aboveground coating system pipeline at NSWCCD before corrosion was initiated.

The plot shows peaks originating from welds, approximately 20 ft apart, as sensed by a transducer mounted in location 2.

Shown in Figure 9 is the summary of the aboveground ultrasonic wave data over time as compared to the baseline with a systematic increase in defect peak height with successive stages of corrosion from a transducer placed at location 2. Waves from one transducer detect the presence of welds, elbows, and one or more defects in the guided wave propagation path. As expected, the signal height depends on the size of the defect, the distance between the transducer and the defect, and the number of welds in the wave propagation path. We note that the noise level increased in the later months as corrosion progressed but was less than 0.1 of the weld signal height at about 80 ft.

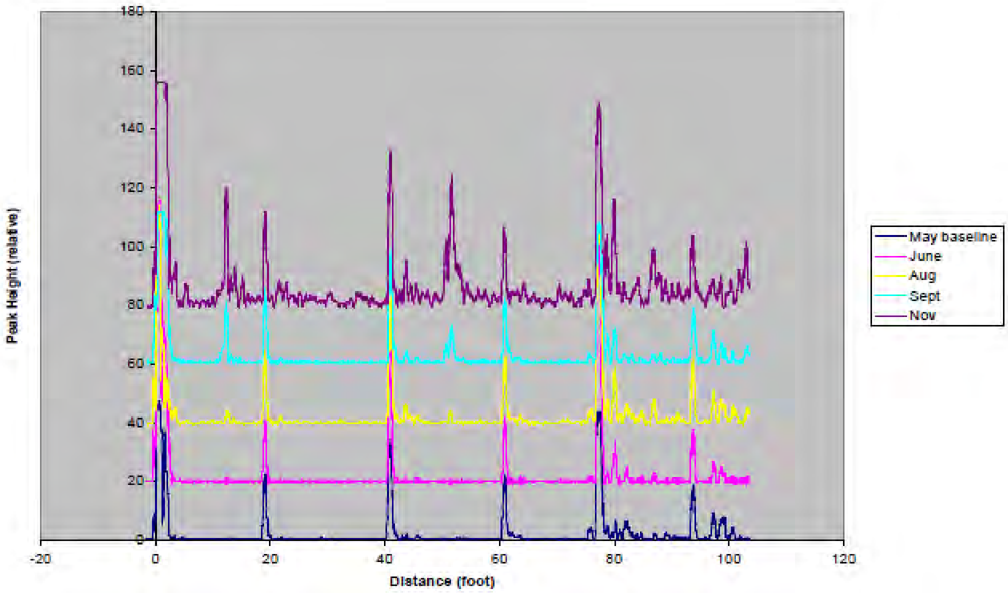

Figure 9. Systematic increases in defect detection over time as compared to the baseline. Systematic increases in peak heights for growing Defects 1 and 2 sensed by transducer at location 2. Defect 1 was located at approximately 50 ft, and Defect 2 was located at approximately 12 ft. The other large peaks, approximately 20 ft apart, are from the welds in the pipeline. The baseline signal (May 2008) is blue, the June signal is pink, the August signal is yellow, the September signal is light blue, and the November signal is purple. An offset of 20 units along the vertical axis has been added to each successive trace before plotting.

7.1.3 Summary of Ultrasonic Results

Three trend lines are shown in Figure 10 to summarize the Phase I results. The solid line is based on all the data obtained in Phase I. It represents an averaged trend that provides an empirical "calibration" curve converting relative signal peak height to percentage CSAL for defects. The other two trend lines (dotted) were generated using the two subsets of data including the effects of an elbow (labeled "18 ft away" in the legend) and the ones representing the largest defects (labeled "25 ft away" in the legend). These two dotted trend lines provide the upper and lower bounds for the slope of the average trend line. Defects with 5% and 10% CSAL produced signal peak height of 0.35 and 0.65 volts, respectively, on the average trend line with uncertainties of approximately 25%. These uncertainties are the results of combining all the data obtained from different transducers, located at distances from 12 to 62 ft from the defect, the existence of a variable number of welds and an elbow, as well as defects of different area, volume, and shape.

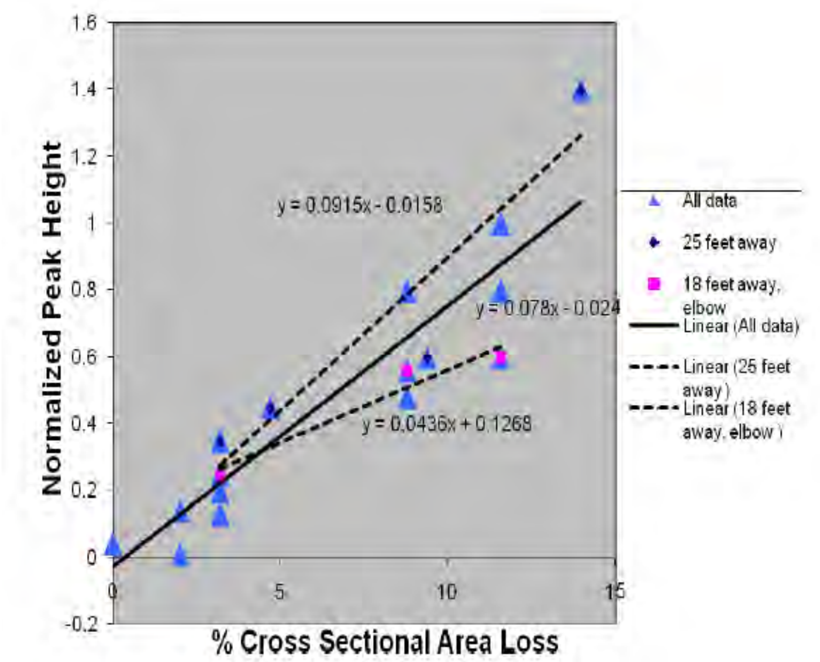

Figure 10. Trend lines for the increase in signal height as the CSAL increases for data obtained in Phase I.

If we focus our attention on the signals associated with a single transducer, as would be appropriate if we are only interested in measuring the changes of the system from a baseline condition, we realize that the slope of the trend line is mainly controlled by the variations of electronic noise and defect shape change over time. The details of the wave propagation across welds and elbows, as well as, scattering mechanisms affecting the absolute signal peak heights are less important when only signal changes are considered, since the effects of these variables (except for the size of the defect) are constant as a function of time. For the purpose of tracking defect growth, we observed in Figure 10 that the slope of the average trend line departs from those represented by the two extremes by no more or less than a factor of 2. Additional discussions of the Phase I results can be found in the Final Report (Liu et. al., 2011a) and a recently published paper (Liu et. al., 2011b).

7.2 FIELD TEST PERFORMANCE EVALUATION (PHASE II)

Three aspects of the pipeline at Norfolk Naval Station greatly affected the technology performance, as demonstrated in the laboratory tests in Phase I. First, in the aboveground vertical pipe sections in Norfolk, where the transducer could be placed, there were usually two or more 90 degree elbows, one ahead and one behind this vertical section. These elbows were there so that the underground and the above ground parts of the pipeline could run parallel to the ground surface (see Figures 6a and 7). Because this vertical section was relatively short, the transducer had to be placed near the ground interface. Experience has shown that the formation of a uniform wave front in the guided wave at 32 kHz required a propagation distance of several feet ahead of the ground interface. This small "lead-in" distance for all the sensors most likely distorted the uniformity of the axisymmetric wave front and attenuated its intensity.

The second important aspect is that pipe sections typically have bends, elbows, valve attachments, and even flanges within the confined space of 5 to 15 ft inside the pit (see Figures 3 and 6b). These features have the following ramifications. First, guided wave cannot propagate across a flange. Its existence prevents the interrogation of the pipe in the direction away from the pit if a transducer cannot be place between the flange and the wall in the valve pit. This was the situation in valve pits 21, 22, and 23 and thus limited wave propagation to one direction only away from the pit. Second, the characteristics of the waves in the forward and the reverse directions generated by one transducer would be very different since the complex components inside the pit strongly modified the waveform in the reverse direction. This had the consequence that attempts to compare the forward to the reverse waves to check for consistency in peak identification, as we did in Phase I, was not successful due to the significant distortions in wave propagation in the reverse direction.

The third aspect is related to the proximity of the water front to most of the pipeline. This resulted in frequent and uncontrollable water saturation inside the valve pits where many of the sensors were located. This was evidenced by the existence of standing water inside these pits and by the grayish marking on the body of the pipe section and on the inside walls of the pits. The tar-based roofing compound probably did not perform as well as anticipated, resulting in deterioration of electrical performance of these sensors and the cable connections. The uncontrollable presence of water in the soil around the underground pipeline also resulted in variable mechanical loading conditions on the pipe, contributing to the instability of the signals over time. These variations would increase further if the conditions of the old protective coating reacted to water unevenly in different parts of the pipeline.

7.2.1 Baseline Data

Key to our demonstration is the comparison of the data traces from the same sensor over the monitoring periods, starting with the baseline data obtained in August 2009, followed by successive stages in January and September of 2010 and April of 2011. Some examples of the baseline traces collected in August 2009 for some of the sensors are shown in Figures 11 and 12.

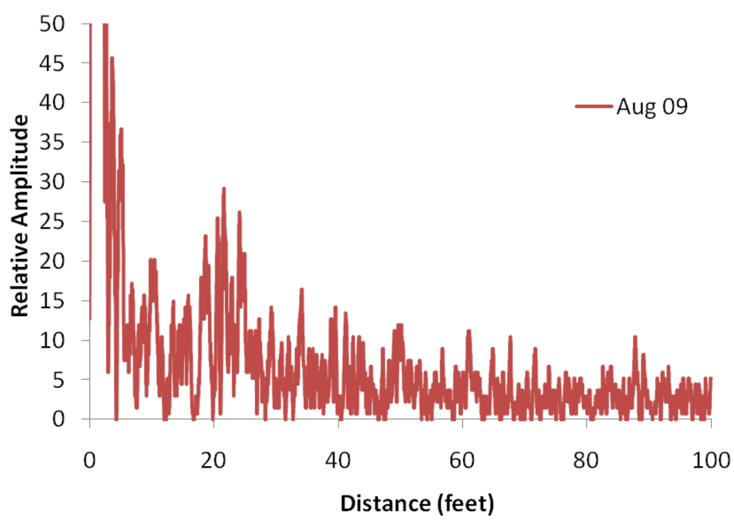

Figure 11. Signal trace at baseline obtained by sensor #22532 inside VP 21 propagating guided waves towards BL 20.

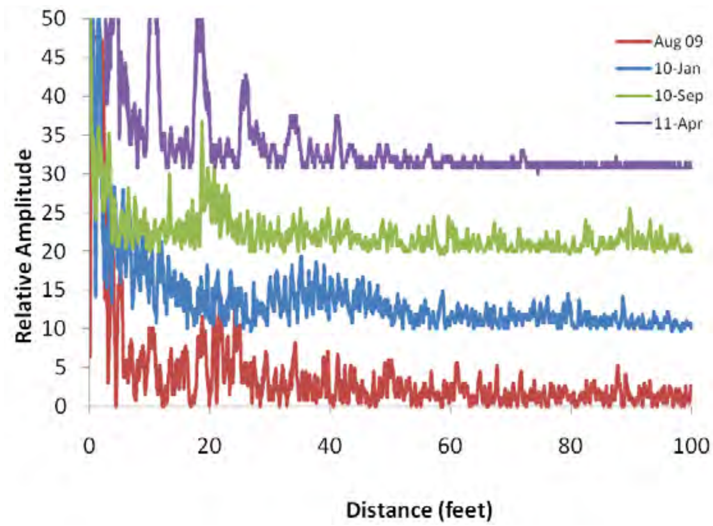

Figure 12. Monitoring changes in data sets obtained at the baseline and successive months by underground sensor #22532.
An offset of 10 units along the vertical axis has been added to each successive trace before plotting.

Shown in Figure 11 is the baseline trace for wave propagation from VP 21 towards BL 20. The peaks located up to 20 ft represent signals, first from the leakage of the transducer excitation, followed successively by the signals at the wall interface, and from welds and reducers along the pipeline. Of note is the pair of peaks above noise level at about 90 ft, which could be identified to originate from the region on the ground where pipe repair and replacement were made a few years back. The height of these two peaks was approximately twice as large as the noise level, which was four times as large as that typically observed in the laboratory tests in Phase I.

In general, we note that while there were apparent peaks above noise level detected at distances beyond 50 ft, most of these large peaks assumed to have originated from welds and elbows were limited to a distance of less than 30 ft. The identification of these signals was greatly hampered by the lack of detailed mechanical drawings for the pipeline layout.

7.2.2 Pipeline Monitoring After Baseline at Norfolk Naval Station

Shown in Figure 12 are traces obtained from the baseline through April 2011 for underground sensor #22532 with wave propagation from VP 21 towards BL 20.

In Figure 12, the data traces collected by an underground sensor (#22532) from the baseline in August 2009 through January 2010, September 2010, and April 2011 are stacked up (with an off-set of 10 units on the vertical axis) to facilitate a comparison of the stability in the peaks detected throughout the course of this project. In particular, the pair of peaks around 90 ft in Figure 12 appeared to be consistently located to within +/-2 ft over the course of 20 months of monitoring. A group of peaks around 60-62 ft appear to be consistently present also.

Data traces in Figure 13 are for waves propagating from VP 5 towards VP 20 from sensor #22506. Focusing on the groups of peaks around 16 ft, 35 ft, and 44 ft, we observe that the

normalized peak heights at some locations (e.g., 35 ft) have not been increasing consistently or they remained relatively unchanged over the course of the monitoring effort. The locations where peak heights remained constant most likely originated from static structural features such as welds. Inconsistent changes in peak heights could be due to signal noise and/or multiple reflections unrelated to defects.

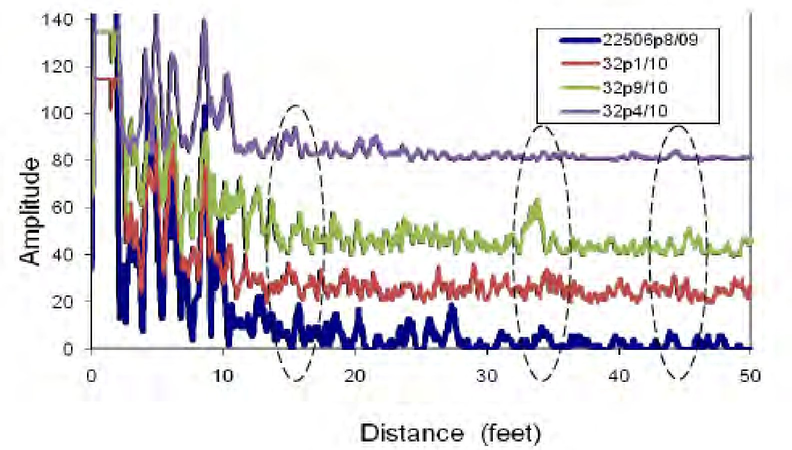

Figure 13. Monitoring signal changes in data sets obtained by aboveground sensor #22506.
An offset of 20 units along the vertical axis has been added to each successive trace before plotting.

The results of the experiment in Phase I are shown in Figure 14. We observed that none of these peaks increased systematically in amplitude during the 20 months of monitoring. Thus, further monitoring is required to determine whether these locations have corrosion-induced defect growth.

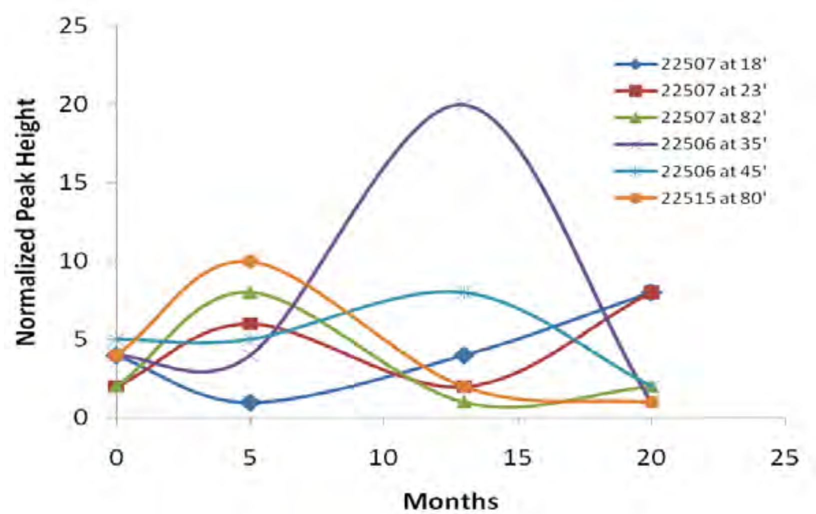

Figure 14. Changes in normalized peak height at suspected defect locations detected by three aboveground transducers.
Typical signal noise was two vertical units.

7.2.3 Performance Assessment (Phase I and II)

The overall test results of the pipeline at Norfolk Naval Station indicate that there has not been significant deterioration as a result of corrosion in the 20 months of this monitoring effort. This is consistent with the fact that there has not been any visible leakage in the pipeline over this period of time. Based on the results obtained in the laboratory and field tests completed thus far, the performance results are enumerated in Table 1.

Since the start of this demonstration in 2008, ultrasonic guided wave technology has been demonstrated in underground pipelines in facilities at Marine Base Quantico, VA, at Mayport Naval Station, Mayport, FL, and on Navy ships at Northrop Grumman Newport News Ship Builders. The potential for defect growth monitoring appears promising in all these locations.

8.0 COST ASSESSMENT

The ultrasonic guided wave measurements are intended to be performed by qualified contractors at DoD fuel farms and pipeline facilities using contractor-owned equipment. Currently, the cost for such services is approximately $2000 per inspector per workday, excluding traveling cost. Because a two-person crew is required working inside VPs, the labor cost for inspecting several pipe sections each 100 ft long should be achievable in one workday at a cost of approximately $4000. Also, because the equipment is contractor-owned, there is little cost associated with hardware procurement and maintenance. Once measurement points are selected, transducers are mounted, and baseline measurements are made, the transducers will remain inactive until the next set of measurements is made months later to monitor changes in the conditions of the pipeline. Each set of such measurements will incur cost at a significantly reduced rate, since the installment of transducers inside valve pits and the service of a safety observer are not required. Ultrasonic guided wave testing should provide timely information on difficult-to-access piping systems at low cost, since many short lines can be tested in one workday at a cost of approximately $2000 per inspector. The real return in investment would be the prevention of serious fuel spills which can cost millions of dollars for cleanup efforts.

8.1 COST MODEL

Table 3. Cost model for technology demonstration at Norfolk Naval Station.

Cost Element	Actual Cost at Norfolk Naval Station	
	Transducer installation/baseline measurement and analysis	**Periodic monitoring and analysis after baseline tests**
Hardware capital costs	$2100 ($300.0 per transducer, 13 installed at 7 VPs)	$0
Inspectors labor	$1200 (600/day for two inspectors)	$600 per day
Data conversion/analysis	$1000 per data collection	$1000 per data collection
Indirect costs (100% of labor)	$1200 ($600/day for two inspectors)	$600 per day
Equipment usage/maintenance	$500/trip	$500 per trip
Equipment shipping	$500/trip	$500 per trip
Travel (San Antonio, TX to Norfolk, VA), time, and expenses	$1000/trip for two inspectors	$1000 per trip
Travel per diem at Norfolk, VA	$640 ($160/person/day for two days)	$160 per day
Safety training/certificates	$1000 ($500/person/job)	$0
On-site equipment van rental	$200 ($100/day for two days)	$100 per day
Facility operational costs		
Environmental safety observer/support (direct and indirect)	$800/job for transducer installation inside VPs	$0
TOTAL	$10,140	$13,380 ($4460 per trip)

8.2 COST ANALYSIS AND COMPARISONS

The ultrasonic guided wave measurements are intended to be performed by qualified inspectors at DoD fuel storage and pipeline facilities using inspector owned equipment. Currently, the cost for such services is approximately $2000 per inspector per workday, excluding traveling cost,

equipment rental, etc. Since the equipment is inspector owned, there is no cost to the government associated with hardware procurement and maintenance.

9.0 IMPLEMENTATION ISSUES

9.1 ISSUES OF SCALING AND TECHNOLOGY TRANSFER

The sections of the pipeline evaluated at Norfolk Naval Station and monitored in the past 20 months are underground. The test design provided access points aboveground to monitor the conditions of these pipes. The results on defect detection and growth monitoring should be applicable for similar pipelines in other DoD facilities. This technology should provide an additional tool for the management of pipeline structural integrity. It should be particularly useful for low-cost condition monitoring at selected locations, such as underground pipes at road crossings or through-tank piping on Navy ships.

Some of the performance objectives have not yet been met in the monitoring duration of 20 months because natural corrosion occurs slowly and since insufficient information is available on the physical construction of the different sections of the pipeline, which could have served as location and defect calibration markers. We recommend that a method to select promising locations for condition monitoring using permanent sensors in a pipeline should be preceded by a preliminary evaluation for weld signal response using remountable transducers. Additionally, locations where weld signals are well above noise level in the baseline would enhance the success of defect growth monitoring later on. Naturally, the more complex the pipe geometry and the longer the pipeline, the more measurement stations will be required at increased cost. Extensive planning for the selection of measurement points is necessary to achieve good results. Mostly, the cost is associated with the labor hours for the testing and subsequent data analysis.

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10.0 REFERENCES

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APPENDIX A

POINTS OF CONTACT

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